# A Quasi-Optical Multiplier for Terahertz Spectroscopy

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The rotational $K$-structure ($K = 0, \ldots 6$) of the a-type transition ($J = 65 \leftarrow 64$) of the symmetric top molecule methylcyanide, $CH_3CN$, has been recorded at 1.2 THz employing a newly designed quasi-optical frequency multiplier. A planar Schottky diode is used as non-linear element for producing the harmonic power and is mounted in the focus of an off-axis antenna across a short single ridged waveguide. The 2nd harmonic of the fundamental frequency is filtered with a dichroic plate and is focused onto the InSb bolometer after passing an absorption cell. The multiplier is driven by a high power backward wave oscillator with a fundamental frequency near 600 GHz.

## Introduction

The submillimeter wave region below a wavelength of $\lambda \geq 0.3$ mm, that is at frequencies above $\nu \geq 1$ THz, remains one of the least explored regions of the electromagnetic spectrum. This is true despite considerable technical efforts to open this part of the spectrum to laboratory and interstellar high resolution spectroscopy, particularly with the advent of space borne astrophysics in the submillimeter region. The increase of density and strength of molecular line intensities with increasing frequency, in conjunction with improved access to many light hydrides in this spectral region, justifies the wide interest and attention the terahertz region receives. Astrophysical molecular transitions at terahertz frequencies occur only in highly excited interstellar regions, and therefore these transitions probe deep into the cores of star formation regions. Technologically, various avenues have been taken for opening the submillimeter wave region for spectroscopy. The principle ones are (i) frequency multiplication of millimeter wave sources, (ii) tunable backward-wave oscillators up to 1.3 THz, and (iii) tunable far infrared sideband laser techniques.

Since the introduction of frequency multiplication by W. Gordy and his collaborators [1], [2], the extension of spectroscopic techniques to shorter wavelengths has been of constant interest. Refinements of the original frequency multiplication techniques [3], [4] and the introduction of InSb hot electron bolometers, have extended high resolution spectroscopy into the terahertz region [3], [5]. The extreme high sensitivity of magnetically tuned InSb bolometers is about 3pW$\sqrt{}$Hz (average NEP) for the range of 1 to 2 THz. Tunable backward wave oscillators (BWOs) as primary radiation sources up to 1.3 THz are now available [6] and have been in use in Russia for some time [7]. Efficient, high-resolution, broadband scanning spectroscopy was recently introduced [8] after the frequency and phase locking of these BWOs at frequencies beyond 1 THz was accomplished. Such systems now compete with the previously available high resolution techniques, namely the use of tunable far-infrared laser spectrometers and Fourier transform spectroscopy. The tunable far IR system initially opened the terahertz region and provides some frequency coverage up to about 6 THz [see e. g. 9]. However, their utility remains limited by the paucity of far infrared laser lines, and their accuracy by that of the laser line positions, which are typically known to within 500 kHz. In best cases the laser line positions are known to within 25 kHz.

Fourier transform spectroscopy is well established in the far IR ($\leq 2$ THz) region, but remains instrument rather than Doppler limited. In addition, the absolute accuracy of the measurement is depending on the availability of calibration lines [10].

## The Cologne Terahertz Spectrometer

For submillimeter wave and terahertz high resolution spectroscopy, wide tunable and low phase noise

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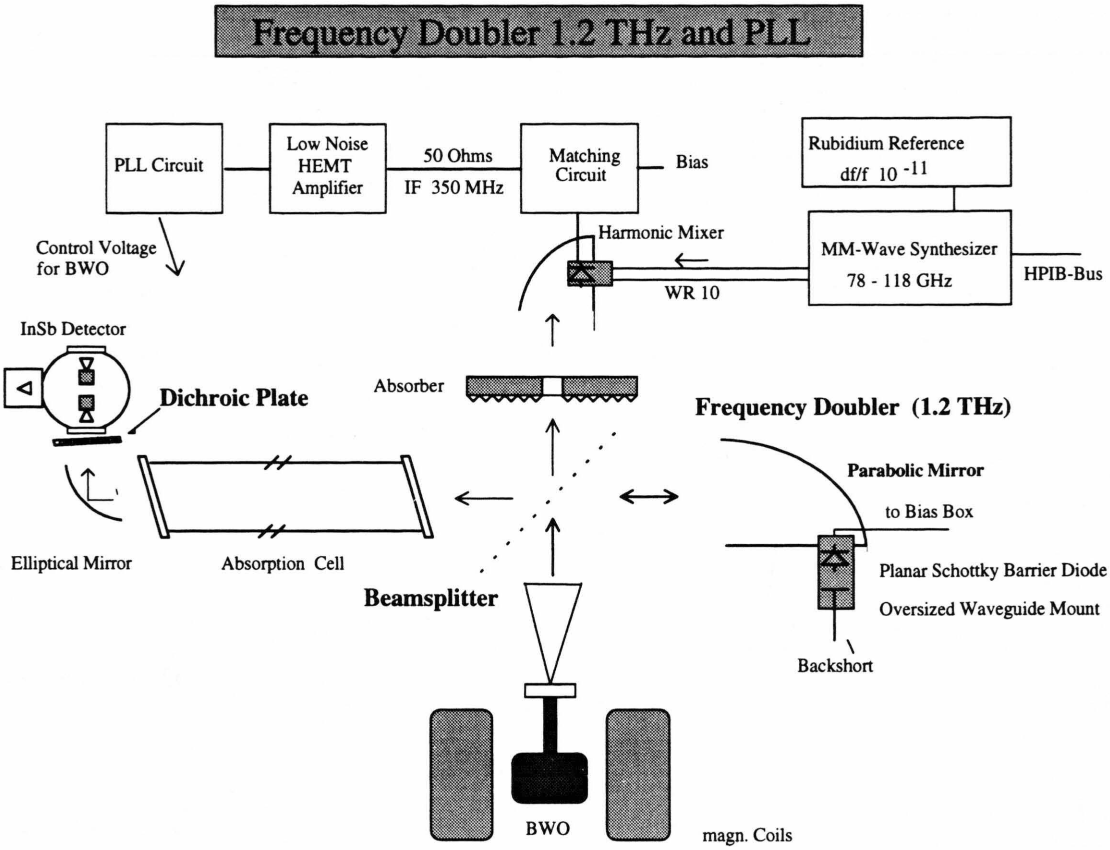


Fig. 1. Quasi-optical frequency doubler for 1.2 THz and phase locked loop circuit.

radiation sources are essential. Early versions of the Cologne Submillimeter Wave Spectrometer, which met these needs, employed phase locked GaAs/InP Gunn oscillators in combination with frequency multipliers. With this spectrometer arrangement frequencies up to 660 GHz were reached. We also installed a carcinotron (Thomson CSF, France) at 220 GHz as the fundamental source, which was used to pump a whisker-contacted varactor diode tripler in the same frequency range [4]. Recently high frequency BWOs (ISTOK Corp., Russia) have been introduced to our spectrometer [8]. These devices offer continuous tunability and high output power covering frequencies beyond 1 THz. In the present communication, we discuss a further extension of the frequency region by a new quasi optical multiplier designed for terahertz operation. First results were obtained by frequency doubling of a 600 GHz BWO, and the recorded transitions of $CH_3CN$ at 1.19 THz are presented.

## Multiplier Design for Terahertz Radiation

Standard multiplier designs use waveguide input coupling and separation of the output waveguide by a coaxial or planar filtering structure. Previous tests [11] of BWO driven tripler/quadrupler at 300 GHz fundamental frequency showed good input coupling (pumped Diode current > 1 mA @ 10 $\mu$A Bias) by use of an overmoded single ridge input waveguide (2.4 mm $\times$ 1.2 mm) combined with an E-H plane tuner. Because of the rapid decrease of the multiplying efficiency at higher harmonics, it seems advantageous in most cases to increase the fundamental frequency. We therefore decided to try frequency multiplication by implementing a high frequency and high power BWO with a center frequency at 590 GHz and a specified maximum output power of 60 mW [Table 1]. The BWO output consists of an overmoded rectangular waveguide (3.6 mm $\times$ 1.8 mm, 70 mm in length),

Table 1. Specified parameters of the 600 GHz backward wave oscillator (Type OB-05).

| Frequency [GHz] | Output Power [mW] | Slow wave structure Voltage [V] | Cathode Current [mA] |
|---|---|---|---|
| 496 | 10 | 2400 | 28 |
| 513 | 20 | 2600 | 29 |
| 550 | 30 | 3000 | 31 |
| 561 | 40 | 3200 | 32 |
| 577 | 50 | 3400 | 33 |
| 588 | 60 | 3600 | 34 |
| 606 | 53 | 3800 | 34.5 |
| 625 | 50 | 4000 | 35 |
| waveguide size: | | 3.6 mm × 1.8 mm | |
| filament power supply: | | 6.3 V (ac) / 1.5 A | |
| magn. field strength: | | 0.9 Tesla | |
| min. lifetime: | | 500 h | |

Table 2. Calculated mesh transmission at 45° incidence angle.

| Frequency [GHz] | Transmission [%] TE Polarization | TM Polarization |
|---|---|---|
| 500 | 12 | 26 |
| 600 | 16 | 34 |
| 700 | 21 | 43 |
| 800 | 27 | 51 |
| 1000 | 39 | 66 |
| 1200 | 53 | 79 |
| 1400 | 67 | 2 |
| 1600 | 83 | 97 |
| 1723 (diffraction limit) | 97 | 4 |

which unfortunately provides only poor matching to the multiplier diode in case the directly connected waveguide technique is used. The oversized output waveguide poses one of the limiting constraints on the single waveguide mode of the BWO, although it is advantageous for high power output and low waveguide attenuation. To overcome this limitation of poor power match to the diode, we employ quasioptical coupling [see Figure 1]. The output power of the BWO is intercepted by a metal mesh which acts as a beamsplitter. At an incident angle of 45° (see Table 2), 16% is transmitted at 600 GHz and feeds a quasi-optical harmonic mixer which supplies a 350 MHz IF signal required for phase locking of the BWO, whereas 83% are deflected via the parabolic mirror onto the planar diode. The 2nd harmonic generated in the planar diode is reflected by the parabolic mirror, passes the beamsplitter with about 53% transmission at 1.2 THz and is focused onto the InSb bolometer after passing the absorption cell and a dichroic plate which rejects most of the remaining fundamental power.

The major function of the mesh is to isolate the output frequency of the doubler from the BWO frequency and to improve input matching due to strong standing waves between the BWO and the doubler. Therefore the distance between BWO and mesh must be carefully adjusted. According to [12], the performance of the mesh can be calculated by using a lumped circuit model that predicts the transmission to within 1% precision. We found that a 250 lines per inch mesh supplied by Buckbee-Mears, Inc. represents a good compromise between reflection loss in the input circuit and transmission loss of the output branch [see Table 2]. The mesh parameters [see Fig. 2] are optically controlled but difficult to determine because of the trapezoidal wire cross section. However, this type of beamsplitter shows excellent broadband performance and low ohmic losses. They have been used successfully for low loss Fabry-Perot interferometers in submillimeter receiver optics in the frequency range 345 - 660 GHz for our radioastrophysical programs [13].

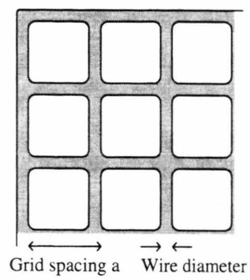


Fig. 2. Two dimensional inductive mesh used as beamsplitter for the THz doubler. The spacing (a) is determined to 102 $\mu$m and the wire diameter (b) is about 12 $\mu$m. The grid is stretched on a 57 mm × 45 mm frame.

Thus one of the important requirements is fulfilled, namely to avoid saturation of the InSb detector with fundamental power. To prevent saturation effects of the bolometer a machined dichroic plate was installed in front of the detector window. The dichroic plate is an equilateral array of circular waveguides, which provide a sharp high pass response [14]. Fundamental radiation is reflectively terminated. The parameters of the dichroic plate are displayed in Figure 3.

The planar Schottky diode is supplied by the Salut Institute (Nizhnii Novgorod, Russia). The junction capacitance is 6 fF and the series resistance about

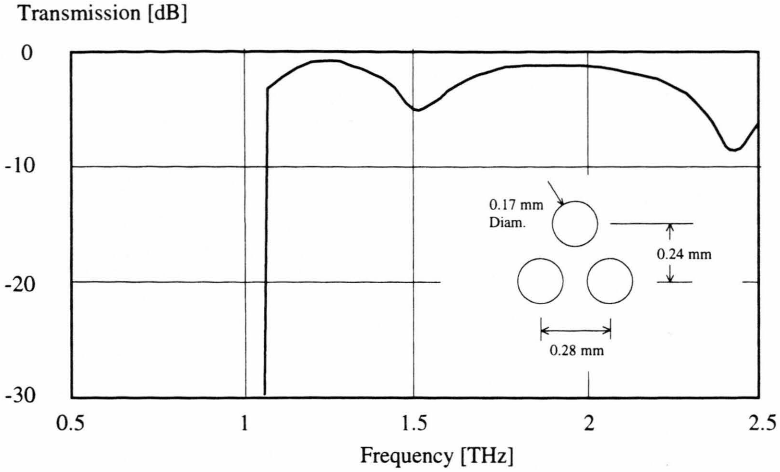


Fig. 3. Calculated transmission curve of the dichroic plate derived from an analysis of the geometry shown in the inset. The diameter of the dichroic plate is about 15 mm, and the number of holes is 2800. The dichroic plate is fabricated of a 0.16 mm thick brass plate with a numerically controlled milling machine. The cut off frequency is 1.03 THz, and the diffraction limit is calculated to be 1.47 THz.

9 Ohms, resulting in a cut off frequency of 2.9 THz. For the design of the planar Schottky diode, the reader is referred to the work of D. G. Paveljev [15]. The diode is mounted in the focus of the parabolic mirror across a short single ridge waveguide forming a gap of 200 $\mu$m. The focus position of the parabolic mirror is adjusted by using an HeNe laser. The mesh orientation is fixed to work in a TE-Polarization mode (E-field perpendicular to the plane of incidence). Even though the polarization of an overmoded waveguide is not fixed, we found that there is a dominant polarization of the BWO radiation which can be identified. Additionally the orientation of the E-field vector is frequency dependent and must be aligned by slightly rotating the doubler. During the measurement of the K-structure of $CH_3CN$ (1 GHz sweep) it was not necessary to readjust the orientation of the doubler. To improve matching of the diode we added a contacting backshort at the back end of the waveguide. The resulting cavity is tuned via a micrometer drive to optimize the diode current. The diode was forward biased with 0.62 V. The maximum current was measured to be 2 mA.

## Spectra at 1.2 THz

As a test and as an example of the performance of the new multiplier operating at the 2nd harmonic, we chose the $J = 65 \leftarrow 64$ rotational transition of $CH_3CN$. This molecule is well studied at lower frequencies (< 1 THz) and the ground state is spectroscopically well understood and characterized. In fact we have measured the rotational spectra of $CH_3CN$ and its two $^{13}C$-isotopomers, $^{13}CH_3CN$ and $CH_3{}^{13}CN$ in the frequency region between 300 and 1050 GHz, and we have determined some of the $\langle P^8 \rangle$ distortion constants. In addition to our previous work, we have measured several molecular absorption lines at 1.2 THz which are of potential astrophysical interest. Figures 4 and 5 illustrate pure rotational transitions of $CH_3CN$ ($J = 65 \leftarrow 64$, $K = 0, \ldots 6$) at 1191 GHz. The absorption lines are shown in second derivative form. The sample pressure was set between 40 and 60 $\mu$bar.

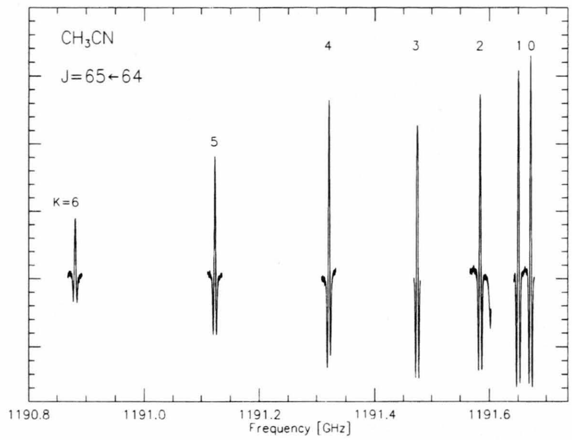


Fig. 4. Display of the first seven low-K components ($K = 0, \ldots 6$) of the $J = 65 \leftarrow 64$ transition of the symmetric-top molecule $CH_3CN$ near 1.19 THz. The $K = 3$ transition, which should be twice as strong due to nuclear spin statistics, was saturated and thereby recorded with smaller response signal.

Figure 4 presents a 1 GHz sweep over the low $K$-structure of the $J = 65 \leftarrow 64$ transition which establishes the presently achievable signal to noise level. The signal to noise ratio of the spectra is determined to be 23 dB. Table 3 shows the present measured line

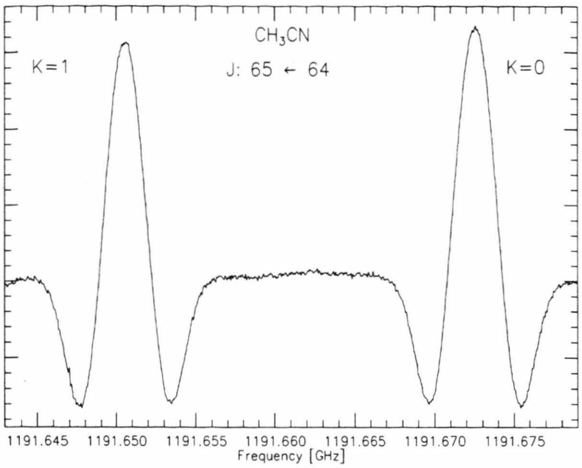


Fig. 5. Expanded view of the $K = 0$ and 1 components. The lines were recorded in second derivative form with a step size of 60 kHz for the second harmonic. The integration time was set to 158 ms per frequency step, with a total number of 600 steps. The peak frequencies were determined to be 1191650.504 and 1191672.494 MHz, respectively, with an estimated error of ±25 kHz.

positions, the estimated accuracy and the achieved diode current of the doubler. Since the high frequency work is in progress we refrain at present from reanalyzing these new data. A complete analysis of our new terahertz data on $CH_3CN$ will be published in due course.

Table 3. $K$ - Structure of $CH_3CN$ ($J = 65 \leftarrow 64$, $K = 0, \ldots 6$) measured with a frequency doubled BWO.

| $K$ | $\nu_{Meas.}$ [MHz] | $\Delta\nu_{Meas.}$ [MHz] | Optimum Diode Bias* |
|---|---|---|---|
| 0 | 1191672,494 | 0.050 | +0.62 V / 1.9 mA |
| 1 | 1191650,504 | 0.050 | +0.62 V / 1.8 mA |
| 2 | 1191584,548 | 0.050 | +0.62 V / 1.8 mA |
| 3 | 1191474,654 | 0.050 | +0.62 V / 1.8 mA |
| 4 | 1191320,904 | 0.050 | +0.62 V / 1.8 mA |
| 5 | 1191123,226 | 0.050 | +0.62 V / 1.4 mA |
| 6 | 1190881,822 | 0.100 | +0.62 V / 1.0 mA |

* Diode forward biased.

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